Canadian Institute of
Guided Ground Transport
Queen's University
at Kingston, Ontario

G W English
C Schwier
J D Young

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CANADIAN RAILWAY MOTIVE POWER: PERFORMANCE TARGETS AND HYBRID BENEFITS EVALUATION

a working paper
prepared for

Transport Canada Transportation Development Centre

by

G.W. English
C. Schwier
J.D. Young

Canadian Institute of Guided Ground Transport
Queen's University at Kingston, Ontario
K7L 3N6

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17. Abstract

The status of various railway motive power alternatives is briefly reviewed. The importance of tractive effort performance and power-per-unit capacities is assessed for Canadian mainline route and service conditions. It was found that adhesion enhancement would benefit Canadian railways in well over half of their freight applications by substantially reducing the number of locomotives required to provide the service. The effectiveness of a principal-electric hybrid locomotive in reducing the fixed costs of electrification is evaluated on a region-specific basis. The findings varied significantly by region. The majority of the potential savings come from avoidance of clearance modification costs. In the case of the Prairies, there are few such restrictions. In the case of the CP Mountain line, while there are a number of expensive clearance restrictions, the gradient over much of the line is too severe to allow significant reduction in tunnel and bridge modification requirements with an auxiliary power system. On the CN Mountain route, there is potential for use of a hybrid locomotive to reduce electrification infrastructure costs. The gradients on this route are such that even a 500-hp-per-locomotive auxiliary on-board power source would provide sufficient power and energy to traverse most of the sidings and overhead obstructions without an overhead contact system. It is recommended that a development program be undertaken to achieve a high-adhesion locomotive truck. It is also recommended that an evaluation of the technical and economic feasibility of an electric hybrid locomotive be undertaken with a view to identifying the potential for a lower cost alternative power source and to identifying price reductions for large volume productions.

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17. Resume

Ce rapport récapitule la situation concernant les diverses possibilités de traction ferroviaire, qu'il évalue en termes de performances et de puissance par locomotive, dans les conditions de service caractéristiques des grandes lignes du Canada. Il montre qu'une augmentation de l'adhérence serait fructueuse dans plus de la moitié des cas de transport ferroviaire de marchandises, réduisant ainsi sensiblemenet le nombre de locomotives devant être attelées. Il évalue, région par région, l'économie réalisable par l'utilisation de locomotives électriques hybrides qui permettent de réduire les frais de premier établissement d'une voie électrifiée. Les résultats obtenus varient considérablement, mais il en ressort que, dans la majorité des cas, la seule façon de réduire les coûts consiste à éviter les réaménagements d'ouvrages d'art existants. Pour la région des Prairies, ce problème n'est pas aigu, le nombre de ponts et de tunnels étant limité. Dans le cas de la ligne de CP Rail traversant les Rocheuses, les réaménagements nécessaires et coûteux sont nombreux et ils ne peuvent être évités que dans de rares cas, les rampes à négocier étant trop raides pour permettre le franchissement de cas tronçons sur le seul moteur auxiliaire. Quant à la ligne correspondante de CN Rail, les possibilités sont bonnes de pouvoir utiliser les locomotives hybrides comme moyen de réduire les coûts d'électrification. En effet, les rampes y sont telles que même un moteur auxiliaire de 500 hp par locomotive donnerait assez de puissance pour franchir la plupart des ponts et des tunnels sans recourir à l'alimentation aérienne. Le rapport recommande donc que soit lancé un programme pour l'étude d'un bogie moteur à haute adhérence. Il préconise aussi une étude de faisabilité technico-économique d'une locomotive hybride, dont le but serait, d'une part, de déterminer si celle-ci constitue effectivement un mode de traction moins coûteux et, d'autre part, de calculer les économies d'échelle qu'apporterait une fabrication en série de cette locomotive.

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1. STATUS OF MOTIVE POWER ALTERNATIVES

The focus of this investigation has been on specific aspects of motive power performance and the attractiveness of a principal electric hybrid locomotive. However, a literature review of the status of the principal motive power alternatives was also undertaken. This section summarizes the findings.

1.1 Diesel Locomotive

Diesel engines used for railway traction have steadily increased in power output over the years. The largest diesel locomotive production model now available in North America is the General Motors SD-50, utilizing a 3,800 hp prime mover. In 1970, Bombardier (then Montreal Locomotive Works) produced a single 4,000 hp locomotive for demonstration purposes.[1] While electric locomotives already possess high power levels, it can be expected that there will be some increases over the near term in diesel-electric power capacities. Several areas by which the output of a diesel engine can be increased have been identified.[2]

By increasing the turbocharger boost pressure of the air used in combustion, power output can be improved. This improvement results in a higher engine combustion pressure, which in turn causes higher mechanical and thermal stresses. To retain engine durability, a more rugged engine design would be required.[3] An increase in the engine shaft rotational speed (while keeping the piston speed constant) would also improve the engine power output.[4] As well, other systems such

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1 Dean, M.W., Hanna, D.B., Canadian Pacific Diesel Locomotives, Railfare Enterprises, Toronto, 1981.

2 Little, S.G., et al., Future Propulsion Systems for Railroad Locomotives, Phase B Report: Advanced Diesel Engines and Alternative Fuels, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 1979.

3 Dean, J.W., "Reliability and High Specific Output -- an American Manufacturer's View," The Next Generation of Diesel Engines for Rail Traction, Institute of Mechanical Engineers, London, U.K., 1982.

4 Gunther, C., "Increased Engine Output," The Next Generation of Diesel Engines for Rail Traction, Institute of Mechanical Engineers, London, U.K., 1982.

as Rankine bottoming cycles and turbocompounding have been investigated. With a Rankine bottoming cycle, waste heat is used to boil an organic liquid, which in turn drives a turbine mechanically coupled to the engine shaft. Turbocompounding utilizes exhaust gas pressure to drive a turbine that is coupled to the engine shaft.

Other systems include the "augmented" diesel and the hyperbar diesel. The former uses a combustor (which burns a mixture of exhaust gas and diesel fuel) to power a gas turbine. Like the turbocompounded engine, the turbine is coupled to the engine. The hyperbar engine uses the combustor and gas turbine to drive the turbocharger compressor to increase the combustion air flow entering the diesel engine. The primary reason for the interest in these diesel engine cycle modifications was to improve the energy efficiency of diesel locomotives. In other words, by making use of the energy lost in the diesel engine exhaust, the fuel consumption for a particular output power level could be reduced; hence, no investigation of the increase in power was made for these systems. Nevertheless, each of these cycles could be used to increase the diesel engine output power level for the same fuel consumption.

1.2 Steam Locomotives

At the end of the steam era, overall efficiency of steam locomotives was in the order of 6 to 7 per cent. Since then, numerous developments have occurred in the area of steam power, primarily for thermal-electric power plants. Current power plants run at a 32 to 35 per cent overall efficiency. By applying these advances to railway use, the possibility of steam-powered locomotives becomes attractive. By using modern combustion processes such as fluidized bed or gas production, with more efficient boilers, efficiencies in the order of 15 per cent have been predicted.[5] Although the 15 per cent thermal efficiency for new-generation steam locomotives is half that of diesel locomotives, they become attractive when the cheaper price for coal is taken into consideration. Modern locomotive steam cycles would use much higher temperatures and pressures than locomotives at the end of

5 Little, S.G., et al., Future Propulsion Systems for Railroad Locomotives, Phase C Report: Alternative Engines and Cost Analysis, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 1979.

the steam era. Also, modern steam locomotives would use a closed-loop cycle. In other words, the exhaust steam would be condensed and recycled through the boiler. General conceptual designs for locomotives have appeared in recent years.[6] Perhaps the most predominant of the renaissance steam locomotives is the American Coal Enterprises ACE 3000. This locomotive utilizes microprocessors to control the boiler and combustion. The standard piston and cylinder reciprocating drive gear of the past are used. The locomotive performance approximates that of a 3,000 hp diesel-electric locomotive. A similar locomotive proposed in England would develop 4000 hp.[7]

Steam turbine powering standard electric transmission equipment (i.e. generator and traction motors) have been constructed and tested over the years: in 1939, two 2,500 hp locomotives by General Electric (scrapped 1942); in 1947, two 6,000 hp locomotives by Westinghouse (scrapped 1950); in 1954, one 4,500 hp locomotive (scrapped 1958).[8]

Two new designs have been put forth: a 2,050 hp "coaltec" locomotive,[9] and a 9,000 hp, 18-axle twin-unit "shoemaker design."[10] As mentioned earlier, these locomotives are only at the conceptual design phase. No hardware development has been carried out to evaluate proposed designs and their performance claims.

1.3 Gas Turbines

Gas turbine locomotives for road freight service were tested in the late 1950s, but were scrapped due to high maintenance costs and the deve-

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6 Armstrong, J.H., "Solid-Fuel Railroading in the '80s?", Railway Age, October 13, 1980.

7 Paul, B., "New Steam Locomotives: A Solution to Imported Fuel?", Modern Railroads, September 1982.

8 Sharpe, J.E., "Rankine Cycle Developments for Rail Traction," Proceedings of the Sixteenth Intersociety Energy Conference, Vol. 2, Atlanta,, Georgia, 1982. ASME Paper #819535.

9 Sharpe, J.E., Coal Burning Locomotives for the 1990s, Queen Mary College, University of London, London, U.K., 1981.

10 Paul, B., op. cit.

lopment of higher horsepower diesel-electric locomotives.[11]

Gas turbine engines were attractive for railway service for two reasons: their ability to burn wide-cut fuels, and their high power-to-weight ratios. As with other alternative propulsion systems, there has been a resurgence of interest in gas turbine locomotives. Efficiencies in the order of 30 per cent have been estimated for gas turbine locomotives driving electric transmissions using present or near-future technology.[12] Improvements in efficiency could be realized if a steam-bottoming cycle was added. With this, the turbine exhaust gas would be used to boil an organic liquid, which, in turn, would drive a steam turbine. The steam turbine could be coupled to gas turbine to increase the output horsepower.[13] Gas turbine's one major drawback is the fact that they have a high idle fuel consumption rate (30 per cent of full load rating), which is substantially greater than the 3 per cent normally associated with diesel-electric locomotives.

1.4 Other Combustion Systems

Other motive power options are currently being investigated. Stirling engines have been under development for a number of years.[14] They are attractive from the point of view that any fuel may be used, but the efficiency of existing Stirling cycles are lower than that of existing diesel locomotives. Substantial development work will be needed because no Stirling engine of the size required for railway applications has been developed. Fuel cells have also been considered for use in locomotives.[15]

Fuel cells produce electricity and are usually one of four basic types: acid, alkaline, molten salt or solid oxide. Since dc current is produced directly by the fuel cell, the locomotive would not carry the

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11 Pinkepank, J., The Second Diesel Spotter's Guide, Kalmbach Publishing, Milwaukee, Wisc., U.S.A., 1973.

12 Little, S.G., et al., op. cit.

13 Communications with James O. Stephens, Gas and Steam Turbine Consultant.

14 Little, S.G., et al., op. cit.

15 Ibid

diesel engine, alternator and rectifier that existing diesel-electric locomotives require. However, a solid-state power-conditioning unit would be required. One major drawback to the fuel cell locomotive is the requirement for storage of hydrogen fuel.

Another motive power option is the natural gas locomotive.[16] Burlington Northern Railroad is currently testing a locomotive converted to burn a mixture of compressed natural gas and diesel fuel. The diesel fuel, in a small proportion, is used to initiate ignition in the diesel engine, which in turn causes the natural gas to combust. A further development would be the use of a spark-ignition engine, designed to burn only natural gas.

1.5 Electrification

The main alternative to on-board generation of power for railway locomotives is electrification. Power is generated at hydraulic or thermal stations and transmitted through an overhead contact system to the locomotive. Without an on-board power plant, the electric locomotive can deliver more power than diesel and other locomotives for the same weight. The absence of an on-board power plant can also result in reduced maintenance and servicing costs -- as much as half of that of present diesel locomotives -- and increased availability and reliablity. There is also a saving in energy costs of electrification compared to the present diesel technology.

In small lots, electric locomotives are more expensive on a unit basis than mass-produced North American diesel-electrics.[17] On a life-cycle basis, however, the lower maintenance requirements and greater availability of the electric make it equal to, or better than, the diesel. If a major electrification program is undertaken, the number of electric locomtives required may be sufficient to result in lower prices. Although electrification substantially reduces net motive power and

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16 Tuskey, Lee, Natural Gas and the Dual Fuel Engine for Locomotives, paper presented at the 46th Annual Conference of the Railway Fuel and Operating Officers Association, Chicago, Ill., September 1983.

17 On a $/hp basis, the electric is lower priced. However, the feasible power levels cannot always be utilized.

energy costs and is a more efficient technology, the costs of providing the overhead contract system and making modifications necessary to achieve physical clearances and electromagnetic compatibility are substantial. Cost estimates range from $150,000 to $324,000 per route-km, depending upon line-specific characteristics. At the present time, the return on such an investment would not be sufficient to attract railway interest.[18]

Many of the motive power developments discussed above can lead to increased power levels. The value of such increases, however, is closely tied to the adhesive ability of the locomotive itself and the site- and service-specific applications. In the next section, the value of important performance attributes is evaluated in relation to Canadian traffic and terrain conditions.

2. DEVELOPMENTS IN LOCOMOTIVE PERFORMANCE

The performance characteristics which most influence locomotive utilization are the power and tractive effort capacities. Power is limited by the weight and volume constraints of the locomotive. For existing mainline locomotives, traction power output ranges from 3,000 hp for diesel-electrics (e.g. SD-40) up to 10,000 hp for electrics (e.g. GM-10B). The tractive effort of a locomotive is limited by the available adhesion between the wheel and the rail, and the space restriction on the traction motors which must produce the required torque. Dispatch levels of adhesion[19] also demonstrate a considerable range. Eighteen per cent is common for conventional diesel-electrics which depend on the natural characteristics of the traction motor for slip recovery. CN uses 22 per cent on locomotives which have been modified with its Positive Traction Control slip recovery feedback control system.

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18 Klein, R., The Potential for Railway Electrification in Canada: The Methodology and Results of a Route-Specific Study, paper delivered to International Centre for Transportation, Amolf, Italy, 1983.

19 That level of adhesion utilization which can be realized with sufficient probability to ascend the most critical grades on a line without having to drop cars.

The General Motors SD-50, with a radar-detected ground speed reference and automatic creep control system, is advertised to achieve a 24 per cent dispatch adhesion level. Lighter-axle-load European electrics are often dispatched at 26 per cent adhesion. This section examines the relative importance of power and adhesion enhancement to the Canadian railways.

Two criteria are used in allocating motive power for train movement. First, the train must have sufficient power to achieve the desired over-the-road travel time for the class of commodity being hauled. The allocation rule is based on the ratio of power-per-ton (total locomotive consist power divided by total train tonnage). Second, the locomotive consist must have sufficient tractive effort and power to haul the train up the steepest grade on the line at the minimum continuous speed rating of the locomotives.

In Canadian railway operations, low-value bulk shipments account for a large proportion of total traffic. For locomotives in bulk commodity service, reliable utilization of adhesion is a constraint to the effective use of higher power capacity. Canadian freight trains have historically received a performance allocation in the range of 0.7 to 2.2 hp/ton. Recent trends, due to escalating fuel costs and capacity constraints, have been to a more uniform power allocation of 1.0 to 1.5 hp/ton.

The effect on transit time of increasing the power-to-weight ratio is illustrated for two train types in Figures 1 through 4. Two general train types were considered in the analysis -- a bulk commodity train and a TOFC ("piggyback") train. The bulk train consisted of 100 hopper cars, each loaded to 130 gross tons. The TOFC train consisted of 86 flat cars, each loaded to 56 gross tons. Both trains had 30-ton vans. Transit times were determined using an analytical train performance model[20] at a variety of locomotive horsepower levels.

Two important effects are evident in these figures. First, there are diminishing returns to increasing power (although there is some vari-

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20 English, G.W., et al., Railway Linehaul Energy Intensity: An Analysis Leading to Design of a Train Simulation Software Package, CIGGT Report No. 80-15, 1981.

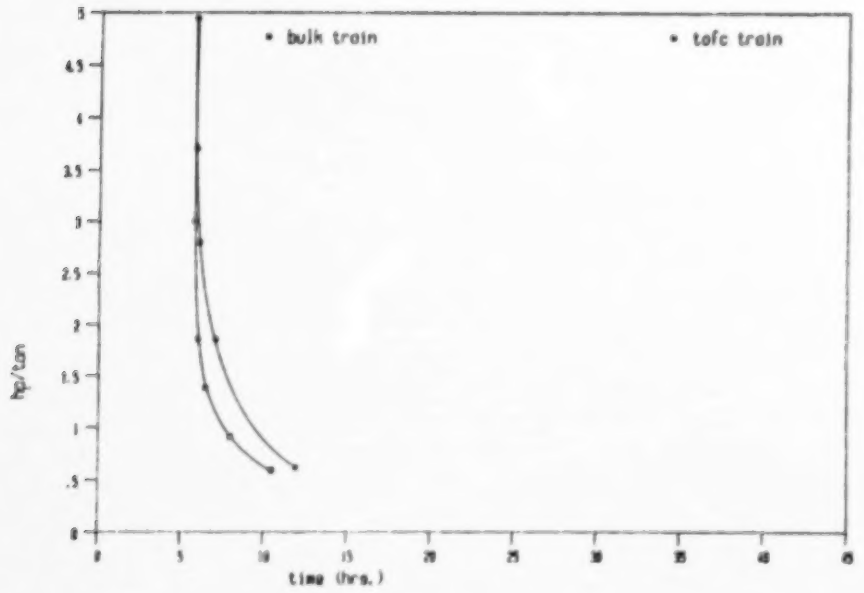

Figure 1 Horsepower per ton versus segment transit time, 330-mile, double-track Corridor segment

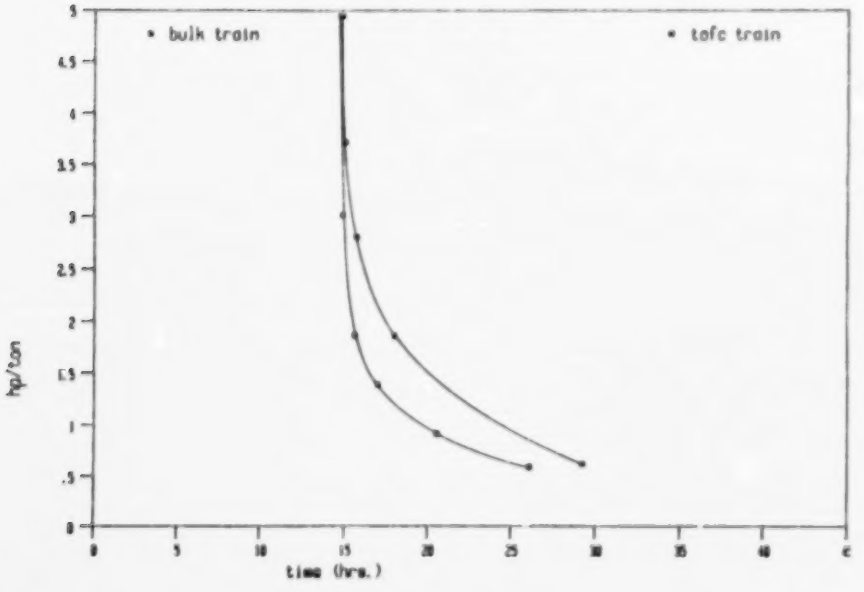

Figure 2 Horsepower per ton versus segment transit time, 794-mile, partial-double-tracked Prairie segment

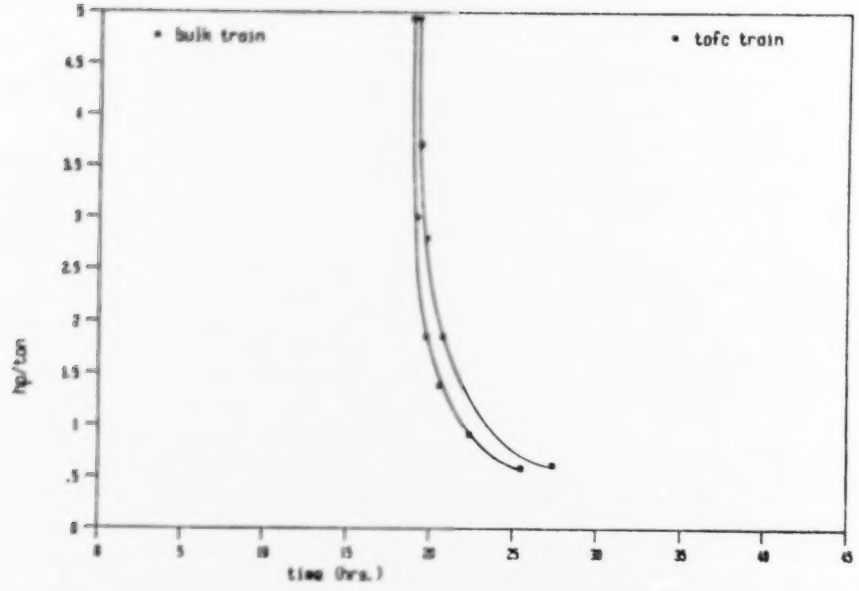

Figure 3 Horsepower per ton versus segment transit time, 645-mile, Mountain segment (high gradients)

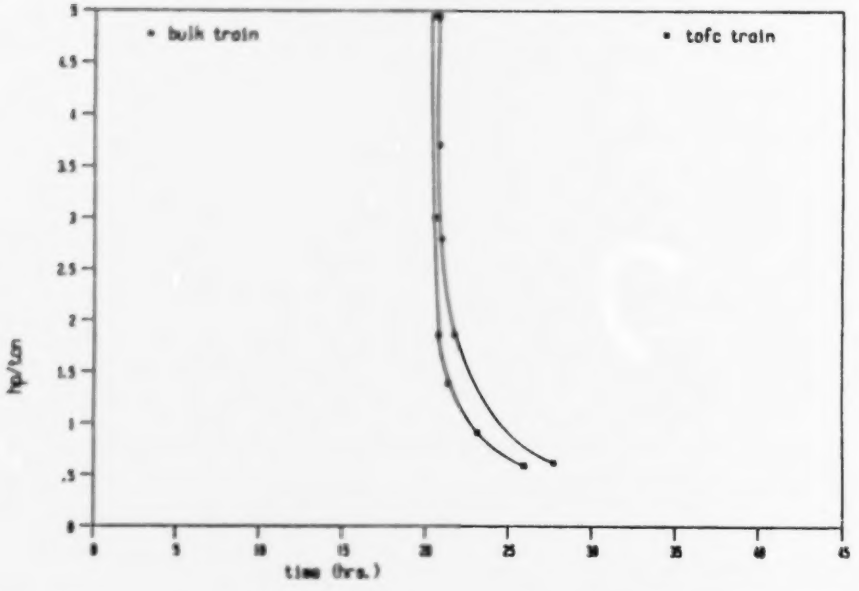

Figure 4 Horsepower per ton versus segment transit time, 748-mile, Mountain segment (low gradients)

ation by region). Second, as the power-to-weight ratio is increased, the lightly-loaded TOFC train requires increasingly more power to achieve the same performance as the heavily loaded bulk train. This is due to the larger drag coefficient for the TOFC train and the increasing role that aerodynamic drag plays at higher speeds. The optimal allocation of motive power is a complex problem involving ill-defined cost relationships (such as the value of time to the shipper, track maintenance costs versus higher speeds, and track capacity costs) as well as the more predictable cost trade-off of energy against equipment utilization. Some increase in the optimal power-to-weight ratio can be expected for lower energy cost options such as electric and natural gas, but this determination is beyond the scope of the present study. On the basis of the diminishing returns illustrated in Figures 1 through 4, it is unlikely that power-to-weight ratios above 1.4 to 1.6 for bulk trains and 2.0 to 2.6 for fast freight trains would be cost-effective.

One of the factors affecting the power assignment for bulk trains is the existing track capacity constraints on some western Canadian main lines. Thus, it is necessary to provide the bulk train with higher-speed capabilities to minimize interference delays, especially to "express" trains on these routes. With the current and planned double-tracking and other capacity-related programs, transit time delays associated with train interference will be reduced. Thus, it may become cost-effective to reduce the power-to-weight ratio for bulk trains in the future.

The desired power level of a locomotive for a specific application depends on the power-to-weight dispatch criterion and the adhesion performance of the locomotive as discussed previously. The adhesion constraint is associated with the steepest grade on the line segment. For mainline segments this "controlling" grade will be about 1.0 per cent for CP's system (after its current gradient reduction program is completed) and 0.6 per cent on some parts of CN's system and 1.0 per cent on others. With compensation for curvature, grades of 1.1 per cent and 0.65 per cent are appropriate values for use in this assessment. The desired power-per-axle of a locomotive is illustrated in Figure 5 for a range of dispatch criteria for these gradients.

The minimum power levels shown are based on an assumed minimum continuous speed of 12 mph. On this basis, power cannot be dispatched below 1.0 hp/ton on a 1.1 per cent grade or below 0.7 hp/ton on a 0.65 per cent grade. An in-depth analysis may show that it would be desirable to have this power rating as a short-term overload rating rather than a continuous rating. The exception to this possibility is CP's mountain line where the grades are such that the train would be in overload for one hour intervals.

Figure 5 illustrates that for bulk trains dispatched at 1.0 hp/ton on a 1.1 per cent grade, the required power per axle (at the railhead) is about 360 hp when adhesion is limited to 0.18, 540 hp at 0.27 adhesion, and 725 hp at 0.36 adhesion. Similarly, if the dispatch power ratio were 2.2 hp/ton, the corresponding power per axle for allowable adhesion would be 785 hp at 0.18, 1,180 hp at 0.27, and 1,570 hp at 0.36. Thus, with a 715 hp/axle capability and a need to dispatch at 1.0 hp/ton over a 1.1 per cent grade, a shift from 0.18 adhesion performance to 0.36 would halve the number of axles required. If a 2.2 hp/ton dispatch criterion were desired, any improvement in adhesion beyond 20 per cent has no effect on the number of axles required.

The power-per-axle data of Figure 5 are translated into locomotive unit capacities in Figure 6. For electric (and gas turbine) locomotives of 6,000 hp capacity, improvements in adhesion of up to 36 per cent could result in corresponding reductions in the number of locomotives required to handle bulk service movements. The 10,000 hp class of locomotive, however, has excessive power for all but fast freight applications, even if 36 per cent adhesion is achieved. Diesel-electric locomotives in the 3,000 hp to 4,000 hp range could benefit from adhesion levels of up to 27 per cent on routes with 1.1 per cent grades and 36 per cent on routes with 0.65 per cent grades when pulling bulk service trains.

The characteristics of new locomotives which would be required by Canadian railways over the next twenty years are determined to a large extent by traffic conditions, the type of services which the railways will provide and the routes over which these services will operate. Table 1 summarizes the projected CN and CP freight traffic

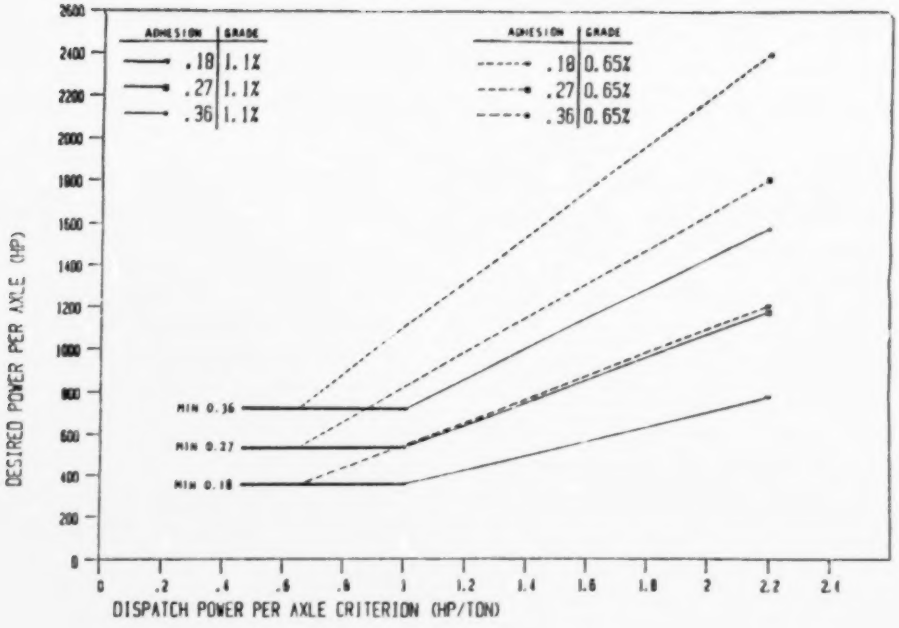

Figure 5 Locomotive power-per-axle requirements

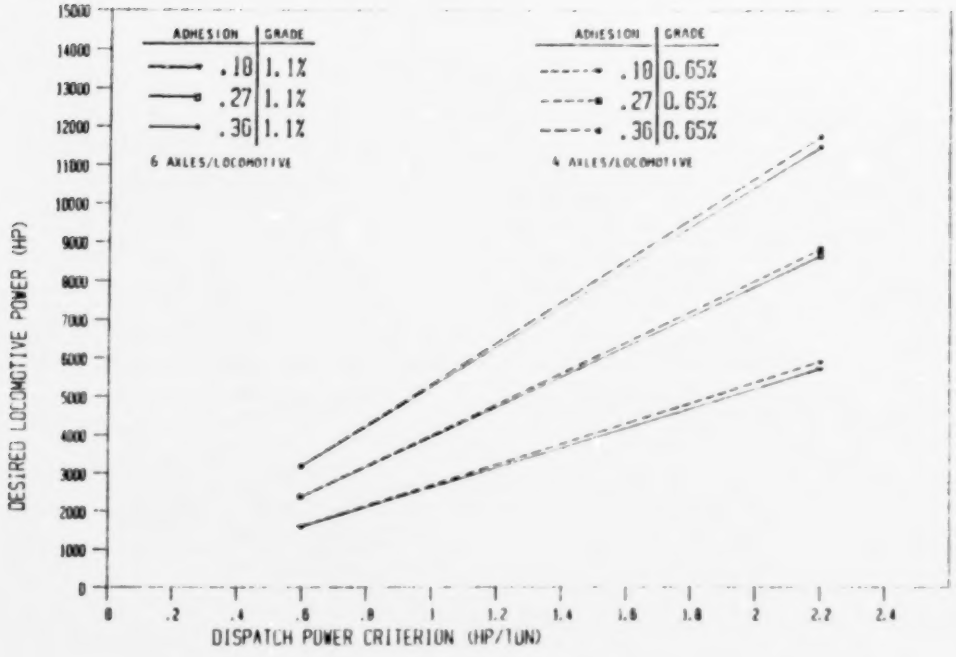

Figure 6 Power-per-locomotive-unit requirements

for the year 1995 made in the National Impacts Study.[21] These figures cover only the major mainline routes, but account for approximately 85 to 90 per cent of total projected traffic.

TABLE 1

YEAR 1995 PROJECTION OF FREIGHT TRAFFIC ON MAJOR ROUTES
(billions of gross ton-miles, CN and CP combined)
(per cent)

	Bulk Freight Service	General Freight Service	Fast Freight Service
1.1 per cent (long) grade	51(14)	17(05)	8(02)
1.1 per cent (short) grade	95(25)	55(15)	42(11)
0.65 per cent grade	45(12)	43(11)	19(05)

From the data shown in Table 1, the dominance of bulk freight service applications is evident. The influence of bulk freight service characteristics is even more pronounced on new locomotive orders, since it can be expected that many of the existing 3,000 hp, 18 per cent adhesion locomotives would be reassigned to general and fast freight services, while new, high-adhesion locomotives would be assigned to bulk freight applications.

Adhesion enhancement would benefit Canadian railways in well over half of their freight applications by substantially reducing the number of locomotives required to provide the service. Since many components of maintenance and servicing are tied to the number of locomotives rather than the work performed, a reduced number of locomotives could also lead to reduced maintenance costs.

21 Empey, W.F., J.A. Osten (Data Resources of Canada), G.W. English, C. Schwier, F.W.A. Bliemel (CIGGT), National Impact of Railway Electrification, June 1983, TP-4461E, prepared for Transport Canada on behalf of the Railway Electrification Committee.

On the other hand, other costs may increase with a move to higher adhesion locomotives. Corneil et al.[22] have noted the possibility of a sharp increase in wear and failure of wheels and rails at higher adhesions if mitigating measures are not taken. A detailed examination of adhesion utilization duty cycles in specific applications is required to evaluate such costs. In addition, a detailed review of the effectiveness of means to enhance adhesion -- such as the chemical treatment and plasma arc procedures which were examined by British Rail -- would be desirable. An evaluation of alternate wheel sizes and metallurgies and their impact on adhesion and wheel strength would also be desirable.

Adhesion enhancement is not just a question of wheel-rail friction. Locomotive traction motors and drive gears must also be able to transmit the necessary torque to the wheel. For Canadian axle loads, the present diesel-electric locomotive truck design will limit the continuous rating of tractive effort. Thus, a systems evaluation of a high-adhesion locomotive truck will also be required.

3. THE USE OF ELECTRIC HYBRID LOCOMOTIVES TO REDUCE THE INFRASTRUCTURE COSTS OF ELECTRIFICATION

Of current interest in the railway sector is the possibility of converting some Canadian main lines to electrified operations. Compared to current diesel operations, electrification offers an opportunity for lower life-cycle motive power costs, and to take advantage of higher adhesion. Since electrification is a long-term, high-cost investment, any decision will need to be made in comparison with the life-cycle costs associated with the motive power developments discussed in Section 1. New-generation diesels, gas turbines and coal-fired steam engines are all **alternatives** to electrification.

One class of motive power development is **complementary** to electrification. This is the dual-mode or hybrid locomotive, which combines the use of externally-generated electricity with some on-board power source.

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22 Corneil, E.R., et al., Electric Locomotive Evaluation, CIGGT Report No. 83-13, March 1984.

Hybrid locomotives for North American railway applications have been evaluated in the past. The Garrett Corporation undertook a feasibility study of a "dual-mode" (diesel electric/straight electric) locomotive on U.S. lines in 1979.[23] The locomotive itself was taken as far as the conceptual design phase. The rationale for the dual-mode locomotive was to stage electrification such that the high energy intensity and high ROI segments of a line could be electrified, while the lower ROI segments would be traversed with diesel power. Garrett also looked at the feasibility of a hybrid yard switcher, using two 4.5 kW-hr flywheels in conjunction with a 1,500 hp diesel-electric locomotive. In addition, there are other methods of providing a second power source, such as gas turbines or small diesel engines.

The focus in this study is on a principal electric hybrid locomotive with a smaller on-board power source. The expected economic returns are in the reduction of the front-end costs of electrification in two areas -- avoidance of clearance costs and reduction of overhead contact wire (OCS) requirements in yards and sidings. In addition, the operating savings could be further increased by allowing shipments from major industrial spurs off the main line to be hauled electrically when on the main line.

The potential for hybrid or dual-mode locomotives to improve the financial prospects of mainline electrification has been examined in four sample situations:

(a) the CN's Montreal-Toronto Corridor route which is characterized by many overhead bridges and a considerable proportion of fast freight traffic

(b) the CN Prairie route (Winnipeg-Edmonton) which is relatively flat and has few overhead obstructions, but a considerable length of passing sidings

(c) the CN Mountain route (Edmonton-Vancouver) which is characterized by both overhead clearance restrictions and sidings, with considerable bulk traffic

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23 Lawson, L.J., L.M. Cook, Dual-Mode Locomotive Systems Engineering (Summary Report), the Garrett Corporation (for the U.S. Federal Railroad Administration), Report No. FRA/ORD-80/82.11, February 1981.

(d) the CP Mountain route (Calgary-Vancouver) which is similar to the CN route but with more severe grades.

The emphasis in this paper is on the potential for reducing the initial infrastructure conversion costs. This does, of course, imply a trade-off with first costs of new electric locomotives. The infrastructure and other costs against which these locomotives are evaluated are those of the National Impact of Railway Electrification Study,[24] updated to 1983 price levels.

3.1 Savings in Clearance Costs

Clearance costs in Canadian railway electrification at 50 kV have been estimated to range from a low of $1,800 per route-km on the prairies to $46,600 per route-km in the mountains. Clearance costs on CN's Toronto-Montreal line could be as high as $20 million.

These costs would be eliminated if the electric locomotives had an on-board power source of sufficient capacity to pull the train across the track segment of concern and handle the locomotive auxiliary power requirements. This clearance modification avoidance requires that the overhead contact system break at bridges and other obstructions.

A system to maintain power at such breaks would work as follows (Figure 7). Initially, wayside transponders signal to the locomotive that an obstruction is approaching. The auxiliary power unit on the locomotive is then automatically brought on line. The auxiliary power unit is "warmed up" until the next transponder is encountered. At this point, the train proceeds through the non-electric section of track with the auxiliary power unit providing limited traction power for the train, as well as power for the air brake compressor, lighting, etc. A non-energized contact wire and a deflection strip under the obstruction guide the pantograph through the non-electrified section so the pantograph on the electric locomotive need not be lowered. Once past the obstruction, the electric locomotive makes contact with the energized overhead system. Wayside transponders bring the electric locomotive propulsion system back on line and shut down the auxiliary power.

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24 Empey, W.F., et al., op. cit.

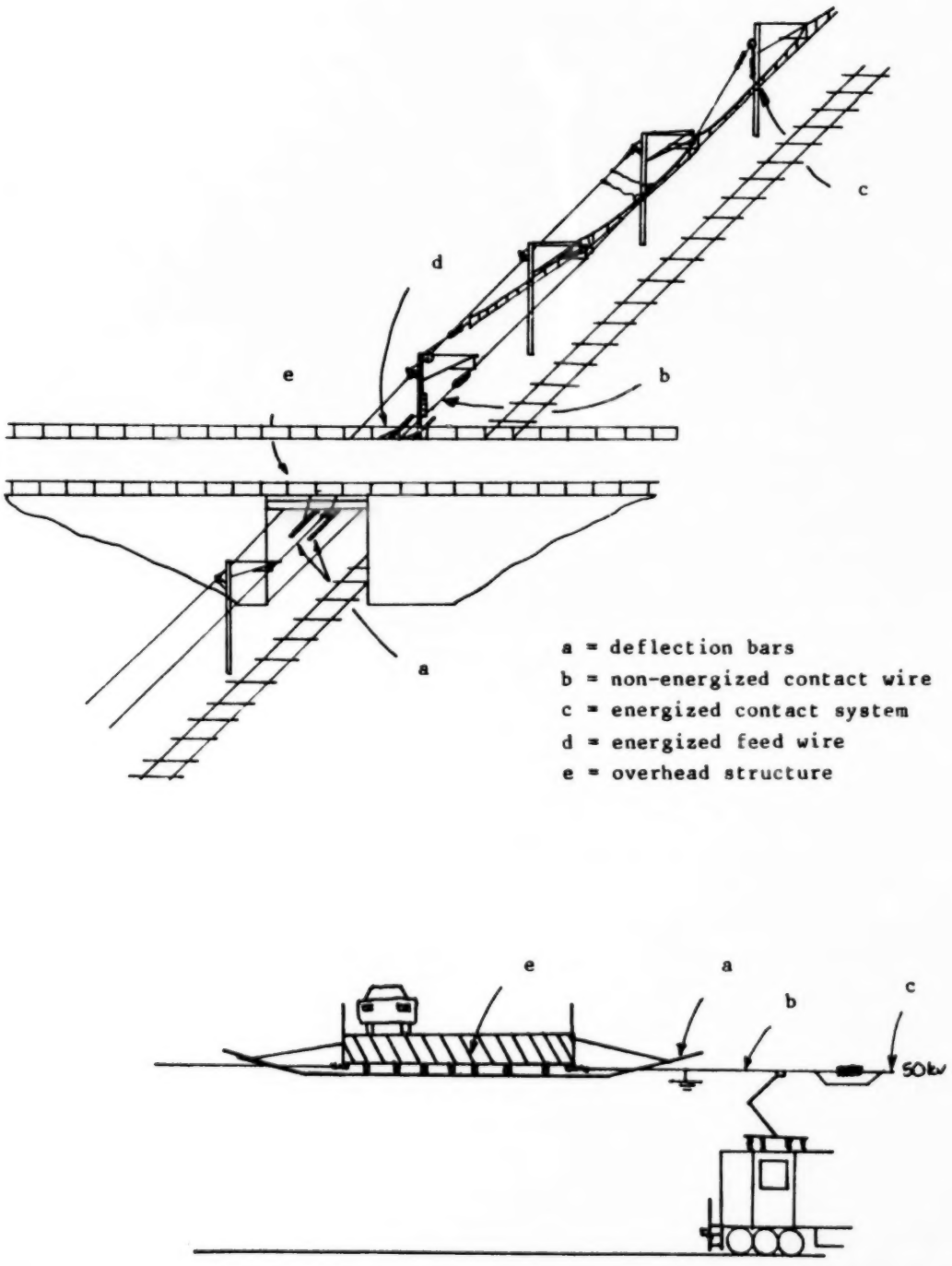
a = deflection bars
b = non-energized contact wire
c = energized contact system
d = energized feed wire
e = overhead structure
50kV

Figure 7 Non-energized contact system for overhead structures

The electric propulsion system thus brings the locomotive back to full speed.

The propulsion power requirement to traverse such discontinuities in the electrified OCS is very sensitive to the type of train and the track conditions at the clearance obstruction. The criteria used to size on-board power requirements allowed the train to recover some of its kinetic energy by decelerating across the track segment. The deceleration was constrained such that coupler forces, if in tension, remained so and the speed of the train was not permitted to fall below 15 mph.

The power requirements associated with a range of gradients and non-powered segment lengths were evaluated for bulk and fast freight types. The results are shown in Table 2. In the Corridor, the bulk train proved to be the limiting case, while in Mountain sections the fast freight running eastbound was found to be the limiting case.

The Montreal-Toronto Corridor and the Mountain routes are the main areas where there is a potential for saving on overhead clearance. On the Prairie route, only 17 overhead obstructions are listed for CN's 1,300 km line.

CN's Montreal-Toronto line has 95 overhead bridges which do not provide 26'0" clearance for 50 kV electrification between the Montreal Yard and Union Station/MacMillan Yard. About 90 per cent of these bridges are isolated. In such cases, it is estimated that about 600 feet would be a sufficient insulated segment length.[25] A requirement of 1,000 feet under on-board power propulsion has been used for calculating purposes to allow for transition from wayside to on-board power and back again. Sixty-five per cent of the bridges are on grades of less than 0.4 per cent, while only 6 per cent of the bridges are on grades greater than 0.8 per cent. Of the bridges that are not isolated, five form a group of closely-spaced bridges over 684 feet (Sources Road) and a pair which are 1,000 feet apart. In both cases, the track gradient is 0.1 per cent

25 One hundred feet for the bridge and 200 feet on either side to take off and terminate the 50 kV feed line.

TABLE 2

POWER AND ENERGY CAPACITY REQUIRED TO TRAVERSE DISCONTINUITIES IN OVERHEAD CONTACT SYSTEM
(hp and hp-hr for propulsion per locomotive consist)

(a) Bulk Train on Corridor Route

Per Cent Grade:	0.0		0.2		0.4		0.6	
Speed:	52.26 mph		34.56 mph		24.12 mph		18.12 mph	
Distance	hp	hp-hr	hp	hp-hr	hr	hp-hr	hp	hp-hr
0.2 miles	1,200	4.623	1,200	7.109	1,200	10.720	6,639	80.1[illegible]
0.4 miles	1,200	9.309	1,200	14.585	1,200	23.647	9,307	224.974
0.6 miles	1,200	14.060	1,200	22.489	3,757	115.270	10,230	370.561
0.8 miles	1,200	18.879	1,200	30.904	5,808	237.669	10,692	515.886
1.0 miles	1,200	23.769	1,200	39.944	7,037	360.254	10,948	660.949
1.2 miles	1,200	28.734	1,200	49.776	7,856	483.024	11,102	806.693
1.4 miles	1,200	33.777	1,200	60.651	8,471	606.623	11,256	951.361
1.6 miles	1,200	38.901	1,200	72.995	8,949	729.967	11,358	1096.041
1.8 miles	1,200	44.112	1,264	92.311	9,290	852.505	11,401	1242.628
2.0 miles	1,200	49.412	2,242	182.499	9,563	975.064	11,461	1390.743

(b) Express Train on Mountain Route

Per Cent Grade:	0.0		0.2		0.4		0.6		0.8		1.0		1.2	
Speed:	30 mph		30 mph		30 mph		28.14 mph		22.98 mph		19.32 mph		16.56 mph	
Distance	hp	hp-hr	hp	hp-hr	hr	hp-hr	hp	hp-hr	hp	hp-hr	hp	hp-hr	hp	hp-hr
0.2 miles	900	6.391	900	6.391	900	6.391	900	6.881	900	8.803	5,323	62.039	7,967	101.231
0.4 miles	900	13.836	900	13.836	900	13.836	900	15.136	4,518	95.109	7,173	167.361	8,495	215.879
0.6 miles	900	23.132	900	23.132	900	23.132	2,139	59.438	6,015	189.609	7,814	272.955	8,665	329.760
0.8 miles	900	32.012	900	32.012	900	32.012	3,863	136.457	6,777	285.327	8,110	378.447	8,749	444.405
1.0 miles	900	40.073	900	40.073	2,038	90.743	4,905	226.994	7,217	380.471	8,307	483.627	8,813	558.408
1.2 miles	900	48.088	900	48.088	2,918	155.911	5,587	310.501	7,540	475.361	8,431	589.015	8,855	671.893
1.4 miles	900	55.939	1,165	72.410	3,570	221.892	6,090	394.271	7,745	570.644	8,505	695.873	8,876	786.545
1.6 miles	900	64.023	1,624	115.526	4,029	286.611	6,198	481.047	7,892	666.847	8,579	800.665	8,897	900.190
1.8 miles	900	71.818	2,007	160.153	4,412	352.067	6,737	561.620	8,039	760.232	8,628	906.550	8,897	1018.957
2.0 miles	900	80.146	2,275	202.592	4,680	416.760	6,952	645.898	8,127	856.891	8,677	1010.335	8,918	1120.121

The per cent clearance obstructions which could be traversed in accordance with the above mentioned deceleration criteria for increasing levels of on-board power and energy are illustrated in Table 3. Approximately 82 per cent of the clearance obstructions in the Corridor are highway overpasses, many in urban areas and/or over major highways involving very long spans. The cost of modifying these bridges for 50 kV compatibility can only be roughly estimated. An average cost of $250,000 per bridge was used for the evaluation. Of the remaining, 7 per cent are through-truss railway bridges estimated to cost $100,000 for modification. Only a handfull are private timber crossings estimated to cost $50,000 for modification. On this basis, the value of power and energy on board is estimated to be on the order of $16 million for the Montreal-Toronto segment with 500 hp units, and $19.5 million with 1,860 hp units.

TABLE 3

FRACTION OF CLEARANCE OBSTRUCTION PROBLEMS ELIMINATED

On-board Capacity		Region				
		CP Mountain		CN Mountain		
Power (hp)	Energy (hp-hr)	Bridges	Tunnels	Bridge	Tunnels	Corridor
500	4.5	20%	21%	100%	100%	75%
1,860	22.4	20%	26%	100%	100%	91%

A similar evaluation was made for CN's Red Pass to Vancouver line and CP's Calgary to Kamloops line. Both lines have a significant number of tunnels but the track gradients differ considerably. For up grades in the loaded direction, 90 per cent of CN's bridges involve gradients of less than 0.4 per cent and all of the tunnels involve gradients of less than 0.2 per cent. On CP's line, most of the bridges are on grades steeper than 0.8 per cent and most of the tunnels are on grades steeper than 2.0 per cent in the backhaul direction. The conditions on CN's line are much more favourable for hybrid operation, as can be seen in Table 3. All of CN's clearance costs could be eliminated with hybrid locomotives of less than 500 hp and 4.5 hp-hr

of on-board propulsion capacity, while only 20 per cent of CP's clearance costs would be eliminated with similar on-board propulsion capacities. Quadrupling the on-board power capacity on the CP line would only gain an extra 4 per cent elimination of clearance problems. The requirements on a per-locomotive basis were calculated on the assumption of 24 per cent adhesion locomotive performance power allocations of 1.0 hp/ton for bulk trains in the loaded direction and 2.6 hp/ton for general freight trains in the backhaul direction, and auxiliary power requirements of 200 hp per locomotive.

On the CN Mountain line, there are 6.25 km of tunnels with restricted overhead clearance for 50 kV electrification. Cost estimates for increasing this clearance average $7,400 (1983$) per metre. On this basis, tunnel savings would be on the order of $46 million. There are approximately 20 overhead structures such as rock sheds or snow sheds with an aggregate length of approximately 500 metres. Using the same cost of modification as used for tunnels, the value of on-board power in these circumstances would be approximately $3.7 million. An average cost of approximately half this value would probably be more realistic, however. There are also six through-truss and at least four other types of bridges with restricted clearances on the route. Since most of these are major structures, the aggregate savings would be on the order of $2 million. Thus, an estimate of the total potential clearance-modification savings from an on-board power source on the CN Mountain route would be approximately $50 million.[26]

On the CP line, a 500 hp power plant would allow a saving of only $1.7 million in tunnels and snowshed modifications. Going to a 1,860 hp power plant could add one 335 m tunnel ($2.5 million) to the list of possible avoided clearance modifications. In either case, only five bridge modifications might be avoided at a maximum saving of $1.3 million.

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26 There are also nine unidentified 22'6" overhead restrictions on the line between Edmonton and Red Pass. Modification of these structures could also be avoided.

3.2 Savings in Sidings

The power required to pull a train into a siding is in general higher than that associated with the clearance conditions analyzed above because the train must slow down before entering the siding, thus losing much of its kinetic energy. The criteria for determining on-board propulsion capacities in sidings was that there must be sufficient on-board power capacity to maintain a speed of 15 mph plus meet auxiliary power requirements on the relevant track gradient, and enough energy capacity to transit two miles in the siding and idle for half an hour with full auxiliary load. The resulting power requirements for a range of gradient conditions are shown in Table 4. The gradient conditions of four line segments were reviewed to determine the effectiveness of increasing power and energy capacities in eliminating the need for an overhead feed line in sidings. The limiting, or worse, case for each of these line segments is summarized in Table 5. From these conditions, the percentage of the sidings which could be operated without an overhead contact system has been determined for a range of on-board power source sizes (Table 6).

The 500 horsepower capacity which was sufficient to eliminate all of the clearance costs in the CN Mountain region is not sufficient to eliminate the need for overhead lines in any of the sidings. About double that power capacity and seven times the energy capacity is required to have a noticeable impact on OCS costs in sidings.

For the purposes of valuing the savings in the OCS system, the costs of the simple, sagged catenary design of the National Impacts Study have been used. On the basis of a detailed cost update undertaken for VIA Rail Canada, the average installed cost of such an OCS for the CN Corridor route would be approximately $100,300 per track/km at 1983 price and wage levels. (This figure includes an allowance for sectioning and other costs associated with electrically connecting sidings to the main line, but excludes allowances for booster transformers.) On the same cost basis, the average installed OCS cost specific to the CN Mountain route would be $110,100 (1983$) per track-km. Costs specific to the CP Mountain route would be $114,100, while costs specific to the CN Prairie route would be $95,200.[27]

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27 Experience with the British Columbia Railway Tumbler Ridge electrification project indicates that OCS costs could be somewhat lower.

TABLE 4

ON-BOARD HORSEPOWER REQUIREMENTS
PER LOCOMOTIVE NEEDED TO TRAVERSE
SIDING WITHOUT OVERHEAD CONTACT SYSTEM

	Gradient					
	0.0	0.2	0.4	0.6	0.8	1.0
Bulk train:						
. three units	648	1,367	2,085	2,803	3,522	4,240
. four units	536	1,075	1,613	2,152	2,691	3,230
Express train:						
. two units	603	1,088	1,573	2,058	2,543	3,027
. three units	469	630	1,115	1,430	1,762	2,085
General freight:						
. three units	570	1,074	1,578	2,082	2,586	3,090
. four units	477	856	1,233	1,611	1,990	2,368

TABLE 5

LOCAL CONDITION ASSUMPTIONS USED
IN DETERMINING AVOIDANCE OF OVERHEAD
CONTACT SYSTEM INSTALLATION USING ON-BOARD POWER

Limiting case	Mountain	Mountain	Prairie	Corridor
Direction	Westbound	Eastbound	Both	Both
Train type	Bulk	General	General	General
Locomotive consist	4	4	3	3

On the CN Corridor route, there are currently 56 km of passing sidings. Given current traffic projections, it is unlikely that this figure would substantially change unless there are signficant changes in VIA's passenger operations. On the CN Prairie single-track route from Winnipeg to Edmonton, there are currently 78 passing loops with an aggregate length of 150 km. Information obtained from CN's Transportation Planning Department indicates that this route would be approximately 50 per cent double-tracked by 1995/2000. Using the mean length and spacing of CN Prairie track, it can be expected that 82 km of the existing single-track passing sidings would be retained. It is not clear what configuration would be adopted for the new double-track sections. It could range from nil to a maximum of 65 km if the siding spacing and length follows that of other CN lines. On the CN Mountain route, there are currently 147 km of passing loops. It is expected that this line will be fully double-tracked between Edmonton and Red Pass, and 50 per cent double-tracked between Red Pass and Vancouver. This would imply a range in aggregate siding length of 49 km to 135 km. Discussions with CP indicate that approximately 135 km of sidings could be expected on its Calgary-Vancouver route by 1995/2000.

On the basis of the proportions of sidings which could be unpowered, (summarized in Table 6) and the foregoing discussion, estimates of the value of an on-board power source are summarized in Table 7.

In addition to sidings, the use of on-board power would also allow the OCS in receiving yards/departure yards and terminals to be substantially reduced. The power level required in these areas is approximately the same as that required for sidings on level terrain. For each of the three sample segments, on the order of 15 km of additional catenary might be avoided with a 900 hp or higher power source. This would be worth approximately $1.5 million on the CN Corridor segment, $1.4 on the CN Prairie segment, $1.6 millon on the CN Mountain route and $1.7 on the CP Mountain segment.

3.3 Value of Electrification Infrastructure Savings per Electric-Hybrid Locomotive

Any savings in the costs of the OCS system at overhead obstructions and on sidings, of course, are only realizable if all of the locomotives used on these modified electrified sections are also modified, at an

TABLE 6

PERCENTAGE OF PASSING SIDINGS NOT REQUIRING OVERHEAD CONTACT SYSTEM DUE TO THE USE OF ON-BOARD POWER

On-board Power Capacity per Locomotive					
Power (hp)	Energy (hp-hrs)	CP Mountain	CN Mountain	CN Prairie	CN Corridor
500	9.5	nil	nil	nil	nil
900	200	25	29	28	35
1,450	390	50	65	58	74
1,980	480	68	97	93	92
2,500	560	77	99.9	99.7	92

TABLE 7

INFRASTRUCTURE CAPITAL SAVINGS ASSOCIATED WITH ELIMINATING OCS IN SIDINGS
(millions of 1983$)

On-board Power Capacity per Locomotive					
Power (hp)	Energy (hp-hrs)	CP Mountain	CN Mountain	CN Prairie	CN Corridor
500	9.5	nil	nil	nil	nil
900	200	3.9	1.6-4.3*	2.2-3.9*	2.0
1,450	390	7.7	3.5-9.7	4.5-8.1	4.2
1,980	480	10.5	5.2-14.4	7.3-13.0	5.2
2,500	560	11.9	5.4-14.8	7.8-14.0	5.2

* range of savings is due to range in siding spacing assumptions

increased cost. A perverse relationship exists in the cost trade-offs. The potential saving in OCS costs is essentially fixed with the line segment, while the added costs of providing on-board power vary directly with the number of locomotives required, and thus with traffic. Higher traffic levels, which in general improve the potential for electrification, tend to decrease the potential for net cost savings attainable by the use of on-board power.

The number of locomotives that would need to be equipped with on-board power for each of the four example sections was determined as in the National Impacts Study. For freight, the following new locomotives are expected to be required:

	1995	1996-2005
CN Corridor route:	39	5
CN Prairie route:	155	13
CN Mountain route:	194	13
CP Mountain route:	242	13

In Table 8, the potential saving in overhead contact system and clearance modification capital costs identified in the previous sections has been recast into the maximum cost -- per locomotive -- of an on-board power source that would leave the net costs of electrification unchanged. This cost includes not only the initial purchase and installation of the power source, but also the discounted present value of the added operating and maintenance costs of these units. No adjustments have been made to reflect differences in relative price levels that are likely to prevail by 1995 as compared to today or for any decrease in locomotive reliability and availability.[28]

28 This could become an important factor. For example, the locomotive requirements for the CN Mountain route were determined using an average of 90 per cent availability. One-half per cent reduction in this for added on-board power plant maintenance could add one unit to the fleet requirement. At $2.3 million each, this reduces the probable cost of an on-board power source by $10,000.

TABLE 8

MAXIMUM COST OF ON-BOARD POWER SOURCE TO JUSTIFY OCS AND CLEARANCE SAVINGS, INCLUDING FIRST COST AND OPERATING/MAINTENANCE COSTS
(thousands of dollars per locomotive unit)

On-board Power Capacity per Locomotive					
Power (hp)	Energy (hp-hrs)	CP Mountain	CN Mountain*	CN Prairie**	CN Corridor
500	9.5	20	270	10	450
900	200	40	280	40	500
1,450	390	50	300	60	560
1,980	480	70	320	80	670
2,500	560	70	320	90	670

* Siding savings taken as the midpoint of the range shown in Table 7.

** Siding savings taken as the midpoint of the range shown in Table 7. In addition, an average savings of $1.5 million for modification to bridges has been included.

As can be seen from Table 8, there is no potential for the use of an on-board source to save electrification infrastructure costs on the Prairies or on the CP Mountain route. The majority of the potential savings come from avoidance of clearance modification costs. In the case of the Prairies, there are few such restrictions. In the case of the CP Mountain line, while there are a number of expensive clearance restrictions, the gradient over much of the line is too severe to allow significant reduction in tunnel and bridge modification requirements with an auxiliary power system. This is the case even with the grade reduction program that CP is currently undertaking. The high gradients also reduce the potential for savings of OCS in passing sidings. This applies to both the CP Mountain section and the CN Prairie route. On the Prairie route, one area that might bear further investigation is the use of a hybrid locomotive for some services where traffic originates or terminates on a light-density line not far off the main line. The number of locomotives over which the savings in OCS costs must be spread must be significantly reduced for on-board power to become justifiable.

On the CN Mountain route, there is a real potential to use a hybrid locomotive to reduce electrification infrastructure costs. The gradients on this route are such that even a 500-hp-per-locomotive auxiliary on-board power source provides sufficient power and energy to traverse most of the sidings and overhead obstructions without an overhead contact system. There could be a net saving if such a power source were to cost no more than $270,000 per locomotive. Minor increases in the capacity of such a unit would not result in any significantly greater savings. Only a 1,500 to 2,000 hp on-board unit would allow for much greater savings in infrastructure costs.

In the CN Corridor route where there are numerous bridges, there is potential for even greater savings, as shown by data in Table 8. There would be net savings if a 500 hp on-board power source cost as much as $450,000. However, these data may overstate the case. The Corridor may not be as desirable a candidate for electrification as other lines because of the lower traffic volume, and thus much higher savings in infrastructure investment costs would be necessary to affect the decision to electrify. Much of the potential for electrification of this line depends on conversion of VIA passenger trains. At current schedule levels, this would require a minimum increase in the hybrid locomotive fleet of 25 per cent, thus decreasing the maximum allowable cost of on-board power to 80 per cent of the level shown in Table 8. Due to the high demand for hotel power on passenger trains, somewhat higher capacity power sources might be required. In addition, the relatively small fleet size required on the Montreal-Toronto line may require a greater percentage of standby locomotives, further reducing the maximum allowable cost of an on-board power source that results in a net saving in electrification investment costs.

3.4 Alternatives for Provision of An On-Board Power Source

The alternative forms of on-board power range from energy storage devices such as batteries and flywheels to diesel or gas turbine engines. The power and energy densities for current and future versions of these options is illustrated in Figure 8. The weight of these alternatives to provide the range of on-board power and energy requirements discussed previously are shown in Table 9. Gas turbine engines are attractive from the standpoint of being compact and having

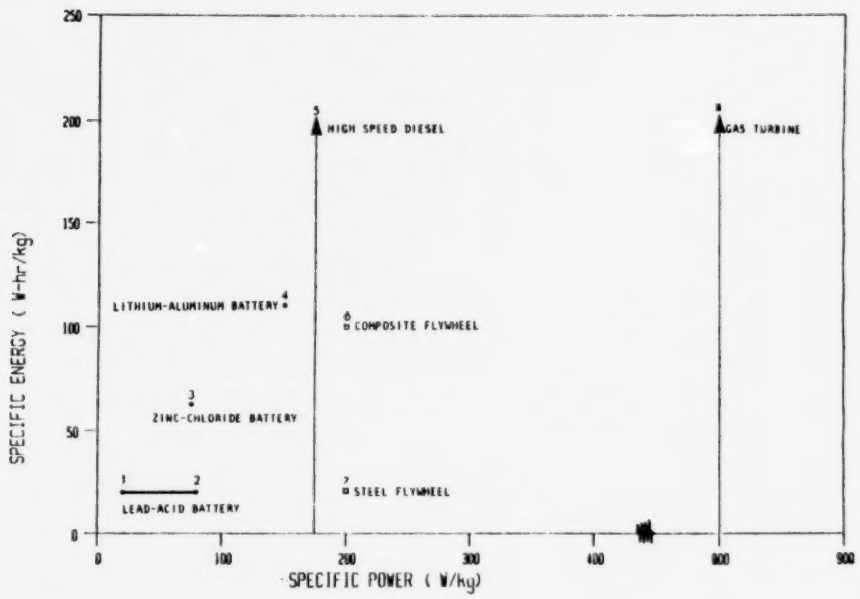

Figure 8 Energy density vs power density for on-board power sources

a high power-to-weight ratio. A major drawback to their use in railway service is a high fuel consumption rate while idling. The idle fuel consumption is 30 per cent of the full power consumption level. (Diesel engines only consume 3 per cent of the full power consumption at idle.) The idle fuel consumption becomes a very significant factor when the very low duty cycle of their potential use as an auxiliary on-board power source is taken into consideration.

For the 500 hp, 4.5 hp-hr capacity which was effective in reducing clearance costs, the power capacity determines the weight for all cases. The conventional steel flywheel energy storage device is attractive in this application. It has no fueling requirements and has low maintenance requirements. The weight shown in Table 9 is, however, just for the storage device itself. The weight of a power conversion device and enclosure must also be considered. The 4.5 hp-hr flywheel proposed in Garrett's flywheel hybrid switcher weighed 3.4 tons, complete with enclosure and alternator. The relevant costs for the flywheel estimated in that study are shown in Table 10 esca-

TABLE 9

POWER SOURCE WEIGHTS FOR
DIFFERENT POWER/ENERGY CAPACITIES
(tons)

Power Source	Power Capacity 400 kW	800 kW	Energy Capacity 5 kWh	500 kWh
Steel flywheel	2	4	.25	25
Composite flywheel	2	4	.05	5
Lead-acid storage battery	8	16	.25	25
Advanced storage battery	3	6	.23	23
High-speed diesel	2.5	5	n/a	n/a
Low-speed diesel	5	10	n/a	n/a
Gas turbine	0.5	1	n/a	n/a

TABLE 10

STEEL FLYWHEEL COST ESTIMATES
(1983$ for a 4.5 hp-hr unit)

Capital Cost:	
Energy Storage Device	$ 134,000
Control equipment	44,600
Installation	40,100
Total	$ 214,700
Annual Operating Costs:	
Energy	$ 600
Maintenance	2,230
Total	$ 2,830
Implied after-tax present value of operating/ maintenance costs over a 30-year life cycle at an 8 per cent real cost of funds	$ 15,300

lated to 1983 dollars. The total life-cycle cost of such a unit would be within the allowable range to result in a net cost savings as identified in Table 8. However, the net savings would not be more than seven or eight million dollars for either the CN Mountain or CN Corridor routes.

For the energy requirements assessed in the siding analysis, one must either go to advanced concepts of flywheel storage using higher speeds and lightweight composite materials, or to primary engines. A 1,200 hp high-speed diesel engine weighs under 5 tons and 500 pounds of fuel would give the locomotive twice the range of existing diesel-electrics for the expected duty cycle. With alternator and fuel tank considered, the total weight would approach 8 tons. The first cost of a diesel engine might be lower than that estimated by Garrett for the flywheel discussed above, but this is offset somewhat by the higher operating costs of the diesel and the implications of fueling and maintenance downtime for locomotive availability.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Locomotive Performance Characteristics

Increases in tractive effort performance to 36 per cent adhesion levels would be of benefit for gas turbine and electric locomotives in a large segment of Canadian railway locomotive applications. In CP's Mountain region, this would have to be a continuous rating but in many other areas it could be a short-term overload rating. For diesel-electric locomotives, power capacities of 4,000 hp could be effectively utilized at 27 per cent adhesion for this segment of motive power applications.

Achievement of higher adhesions requires detailed systems development of the complete locomotive truck and must consider the implications for maintenance reliability and the forces imparted to the track. It is recommended that such a development program be undertaken.

4.2 Hybrid Locomotives

A hybrid electric locomotive with 500 hp on-board power capacity and a 4.5 hp-hr energy capacity (per application) would permit a train without an overhead power supply to pass under many clearance

obstructions while maintaining coupler tension. The cost saving potential to be realized by not raising bridges and tunnels on electrified lines is substantial. However, these savings are largely offset by the cost of the on-board power plant. The power requirements are such that tripling the overload power has very little incremental impact.

The power and energy requirements can be met by a steel flywheel energy storage device weighing 3.4 tons. A preliminary economic evaluation indicates such a flywheel hybrid would be economical in some regions of Canada if electrification was undertaken there. It would not substantially alter the electrification decision, except in very marginal cases.

It is recommended that an evaluation of the technical and economic feasibility of an electric hybrid locomotive be undertaken with a view to identifying the potential for a lower-cost alternative power source and to identifying price reductions for large-volume productions. Such an evaluation would need to be predicated on a decision to electrify or evidence that electrification may be marginally attractive.

Given the differential impact of technical developments in adhesion performance and hybrid capacity on different locomotive alternatives, it is recommended that the comparative evaluation of the full range of motive power alternatives be undertaken for Canadian application with consideration of these potential developments.